

Description

[RETRIEVABLE SUBSURFACE NUCLEAR LOGGING SYSTEM]

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of U.S. Patent Application Serial No. 10/355,599, filed January 30, 2003, which is a divisional of U.S. Patent Application Serial No. 09/576,271, filed May 22, 2000.

BACKGROUND OF INVENTION

[0002] *Field of the Invention*

[0003] This invention relates generally to investigation of subsurface earth formations, and, more particularly, to techniques for determining formation properties using a well tool equipped with radiation sources and adapted for conveyance into and retrieval from a downhole tubular.

[0004] *Description of Related Art*

[0005] Resistivity and gamma-ray logging are the two formation evaluation measurements run most often in well logging.

Such measurements are used to locate and evaluate the properties of potential hydrocarbon bearing zones in subsurface formations. In many wells, they are the only two measurements performed, particularly in low cost wells and in surface and intermediate sections of more expensive wells.

[0006] These logging techniques are realized in different ways. A well tool, comprising a number of transmitting and detecting devices for measuring various parameters, can be lowered into a borehole on the end of a cable, or wireline. The cable, which is attached to some sort of mobile processing center at the surface, is the means by which parameter data is sent up to the surface. With this type of wireline logging, it becomes possible to measure borehole and formation parameters as a function of depth, i.e., while the tool is being pulled uphole.

[0007] Some wells may not be logged because wireline logging is too expensive, when rig time is included in the total cost. Conditioning the well for wireline logging, rigging up the wireline tools, and the time to run the wireline tools in and out require rig time. Horizontal or deviated wells also present increased cost and difficulty for the use of wireline tools.

[0008] An alternative to wireline logging techniques is the collection of data on downhole conditions during the drilling process. By collecting and processing such information during the drilling process, the driller can modify or correct key steps of the operation to optimize performance. Schemes for collecting data of downhole conditions and movement of the drilling assembly during the drilling operation are known as Measurement While Drilling (MWD) techniques. Similar techniques focusing more on measurement of formation parameters than on movement of the drilling assembly are known as Logging While Drilling (LWD). As with wireline logging, the use of LWD and MWD tools may not be justified due to the cost of the equipment and the associated service since the tools are in the hole for the entire time it takes to drill the section.

[0009] Logging While Tripping (LWT) presents a cost-effective alternative to LWD and MWD techniques. In LWT, a small diameter "run-in" tool is sent downhole through the drill pipe, at the end of a bit run, just before the drill pipe is pulled. The run-in tool is used to measure the downhole physical quantities as the drill string is extracted or tripped out of the hole. Measured data is recorded into tool memory versus time during the trip out. At the sur-

face, a second set of equipment records bit depth versus time for the trip out, and this allows the measurements to be placed on depth.

[0010] U.S. Pat. No. 5,589,825 describes a LWT technique incorporating a logging tool adapted for movement through a drillstring and into a drilling sub. The '825 patent describes a sub incorporating a window mechanism to permit signal communication between a housed logging tool and the wellbore. The window mechanism is operable between an open and closed position. A disadvantage of the proposed apparatus is that the open-window mechanism directly exposes the logging tool to the rugose and abrasive borehole environment, where formation cuttings are likely to damage the logging tool and jam the window mechanism. Downhole conditions progressively become more hostile at greater depths. At depths of 5,000 to 8,000 meters, bottom hole temperatures of 260°C and pressures of 170 Mpa are often encountered. This exacerbates degradation of external or exposed logging tool components. Thus, an open-window structure is impractical for use in a downhole environment.

[0011] UK Patent Application GB 2337546A describes a composite structure incorporated within a drill collar to permit the

passage of electromagnetic energy for use in measurements during the drilling operation. The '546 application describes a drill collar having voids or recesses with embedded composite covers. A disadvantage of the apparatus proposed by the '546 application is the use of composite materials as an integral part of the drill collar. Fatigue loading (i.e., the bending and rotating of the drill pipe) becomes an issue in drilling operations. When the drill pipe is subjected to bending or torsion, the shapes of the voids or recesses change, resulting in stress failure and poor sealing. The differences in material properties between the metal and composite covers are difficult to manage properly where the composite and metal are required to act mechanically as one piece, such as described in the '546 application. Thus, the increased propensity for failure under the extreme stresses and loading encountered during drilling operations makes implementation of the described structure impractical.

[0012] U.S. Pats. Nos. 5,988,300 and 5,944,124 describe a composite tube structure adapted for use in a drillstring. The '300 and '124 patents describe a piecewise structure including a composite tube assembled with end-fittings and an outer wrapping connecting the tube with the end-

fittings. In addition to high manufacturing costs, another disadvantage of this structure is that the multi-part assembly is more prone to failure under the extreme stresses encountered during drilling operations.

[0013] U.S. Pat. No. 5,939,885 describes a well logging apparatus including a mounting member equipped with coil antennas and housed within a slotted drill collar. However, the apparatus is not designed for LWT operations. U.S. Pats. Nos. 4,041,780 and 4,047,430 describe a logging instrument that is pumped down into a drill pipe for obtaining logging samples. However, the system proposed by the '780 and '430 patents requires the withdrawal of the entire drill string (for removal of the drill bit) before any logging may be commenced. Thus, implementation of the described system is impractical and not cost effective for many operations.

[0014] U.S. Pat. No. 5,560,437 describes a telemetry method and apparatus for obtaining measurements of downhole parameters. The '437 patent describes a logging probe that is ejected into the drill string. The logging probe includes a sensor at one end that is positioned through an aperture in a special drill bit at the end of the drill string. As such, the sensor has direct access to the drill bore. A disadvan-

tage of the apparatus proposed by the '437 patent is the sensor's direct exposure to the damaging conditions encountered downhole. The use of a small probe protruding through a small aperture is also impractical for resistivity logging.

[0015] U.S. Pat. No. 4,914,637 describes a downhole tool adapted for deployment from the surface through the drill string to a desired location in the conduit. A modulator on the tool transmits gathered signal data to the surface. U.S. Pat. No. 5,050,675 (assigned to the present assignee) describes a perforating apparatus incorporating an inductive coupler configuration for signal communication between the surface and the downhole tool. U.S. Pat. No. 5,455,573 describes an inductive coupling device for coaxially arranged downhole tools. Downhole techniques have also been proposed utilizing slotted tubes. U.S. Pat. No. 5,372,208 describes the use of slotted tube sections as part of a drill string to sample ground water during drilling. However, none of these proposed systems relate to through-tubing measurement or signal transfer.

[0016] While LWT techniques incorporating neutron and gamma-ray measurements have been proposed in the market, these designs are not optimized for formation evaluation.

A need remains for simplified, reliable, and retrievable radiation-source systems for locating and evaluating the properties of potential hydrocarbon bearing zones in subsurface formations.

SUMMARY OF INVENTION

[0017] The invention provides a system for determining a property of a subsurface formation traversed by a borehole. The system comprises a sub having an elongated body with tubular walls and an inner bore, the sub adapted for disposal within the borehole; a run-in tool adapted for disposal within the sub bore; and the run-in tool having at least one radiation source or at least one radiation sensor disposed thereon; wherein the sub wall includes an inner passage adapted to direct radiation energy emitted from within the sub back toward the sub bore.

[0018] The invention provides a system for determining a property of a subsurface formation traversed by a borehole. The system comprises a sub having an elongated body with tubular walls and an inner bore, the sub adapted for disposal within the borehole; the sub including at least one fully penetrating opening and at least one partially penetrating window along the tubular wall; the sub including a pressure barrier between the interior and exte-

rior of the tubular wall at the at least one fully penetrating opening; a run-in tool adapted for disposal within the sub bore; the run-in tool including at least one radiation source or at least one radiation sensor; wherein at least one radiation source or at least one radiation sensor on the run-in tool is located near a partially penetrating window on the sub when said tool is disposed within the sub; and the sub wall including an inner passage adapted to direct radiation energy emitted from within the sub back toward the sub bore.

[0019] The invention provides a method for determining a property of a subsurface formation traversed by a borehole. The method comprises adapting a sub for disposal within the borehole, the sub having an elongated body with tubular walls and an inner bore, the sub wall including an inner passage adapted to direct radiation energy emitted from within the sub back toward the sub bore; disposing a run-in tool within the sub bore, said tool having at least one radiation source and at least one radiation sensor disposed thereon; emitting radiation energy into the formation from the at least one radiation source on the run-in tool; and detecting radiation energy with the at least one radiation sensor on the run-in tool to determine the

formation property.

BRIEF DESCRIPTION OF DRAWINGS

- [0020] Other aspects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:
- [0021] FIG. 1 is a schematic diagram of a run-in tool in accord with the invention.
- [0022] FIG. 2a is a cross-sectional view of a run-in tool showing an antenna with associated wiring and passages in accord with the invention.
- [0023] FIG. 2b is a schematic diagram of a shield structure surrounding an antenna on the run-in tool in accord with the invention.
- [0024] FIG. 3 is a schematic diagram of a tubular member with slotted stations in accord with the invention.
- [0025] FIGS. 4a and 4b are schematic diagrams of a run-in tool engaged within a tubular member in accord with the invention. FIG. 5 graphically illustrates the relationship between the slot dimensions of a tubular segment of the invention and the attenuation of passing electromagnetic energy.
- [0026] FIG. 6 is a schematic diagram of a run-in tool with a centralizer configuration in accord with the invention.

[0027] FIG. 7a is a cross-sectional view of a tubular member with a pressure barrier configuration in accord with the invention.

[0028] FIG. 7b is a cross-sectional view of a three-slotted tubular member of FIG. 7a along line A-A.

[0029] FIG. 8a is a cross-sectional view of a tubular member with another pressure barrier configuration in accord with the invention.

[0030] FIG. 8b is a cross-sectional view of a three-slotted tubular member of FIG. 8a along line B-B.

[0031] FIG. 9a is a cross-sectional view of a run-in tool positioned in alignment with a pressure barrier configuration in accord with the invention.

[0032] FIG. 9b is a top view of the run-in tool and pressure barrier configuration of FIG. 9a.

[0033] FIG. 10 is a cross-sectional view of a pressure barrier and tubular member configuration in accord with the invention.

[0034] FIG. 11 is a cross-sectional view of a slotted tubular member with an insert, seal, and retaining sleeve in accord with the invention.

[0035] FIGS. 12a and 12b are cross-sectional views and cut-away perspectives of a slotted tubular station with a tapered

slot and a corresponding tapered insert in accord with the invention.

[0036] FIG. 13a is a schematic diagram of a run-in tool and antenna eccentric within a tubular member in accord with the invention.

[0037] FIGS. 13b and 13c are schematic diagrams of a run-in tool and antenna surrounded by a focusing shield and respectively showing the shield's effect on the magnetic and electric fields in accord with the invention.

[0038] FIG. 14 is a top view of a shielding structure formed within the bore of the tubular member in accord with the invention.

[0039] FIG. 15 is a schematic diagram of a shielding structure formed by a cavity within the run-in tool in accord with the invention.

[0040] FIG. 16 is a schematic diagram of a run-in tool including a modulator engaged within a tubular member in accord with the invention.

[0041] FIG. 17 is a schematic diagram of the run-in tool configuration of FIG. 16 as used for real-time wireless communication with a remote downhole tool in accord with invention.

[0042] FIG. 18 is a schematic diagram of a run-in tool configura-

tion for porosity measurements utilizing magnetic nuclear resonance techniques in accord with the invention.

[0043] FIGS. 19a and 19b are schematic diagrams of run-in tool antenna configurations within tubular members in accord with the invention.

[0044] FIG. 20 shows schematic diagrams of a tubular member and run-in tool configuration with inductive couplers in accord with the invention.

[0045] FIG. 21 shows a top view and a schematic diagram and of an eccentric run-in tool and tubular member with inductive couplers in accord with the invention.

[0046] FIGS. 22a and 22b are schematic diagrams of an inductive coupler configuration within a run-in tool and tubular member in accord with the invention.

[0047] FIG. 23 is a cross-sectional view of an inductive coupler and shield configuration mounted within a tubular member in accord with the invention.

[0048] FIG. 24 is a schematic diagram of a simplified inductive coupler circuit in accord with the invention.

[0049] FIG. 25 is a flow chart illustrating a method for transmitting and/or receiving a signal through an earth formation in accord with the invention.

[0050] FIG. 26 is a flow chart illustrating a method for measuring

a characteristic of an earth formation surrounding a borehole in accord with the invention.

[0051] FIG. 27 is a flow chart illustrating a method for sealing an opening on the surface of a tubular member in accord with the invention.

[0052] FIG. 28 is a flow chart illustrating a method for sealing a fully penetrating opening on a surface of a tubular member in accord with the invention.

[0053] FIG. 29 is a schematic diagram of a run-in tool equipped with radiation sources/sensors and engaged within a tubular in accord with the invention.

[0054] FIG. 30 is a longitudinal cross-sectional view of a segment of the run-in tool and tubular of FIG. 29.

[0055] FIG. 31 is a transverse cross-sectional view of the run-in tool of FIG. 30 disposed within the tubular.

[0056] FIG. 32 is a schematic diagram of a run-in tool equipped with position-sensitive radiation sensors and engaged within a tubular in accord with the invention.

[0057] FIG. 33 graphically illustrates functions derived using the position-sensitive sensors of FIG. 32 and derived ratios used for measurement calibration in accord with the invention.

[0058] FIG. 34 is a flow chart illustrating a method for determin-

ing a property of a subsurface formation in accord with the invention.

DETAILED DESCRIPTION

[0059] In the interest of clarity, not all features of actual implementation are described in this specification. It will be appreciated that although the development of any such actual implementation might be complex and time-consuming, it would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

[0060] The apparatus of the invention consists of two main assets, a run-in tool (RIT) and a drill collar. Henceforth, the drill collar will be referred to as the sub.

[0061] *RIT* FIG. 1 shows an embodiment of the RIT 10 of the invention. The RIT 10 is an elongated, small-diameter, metal mandrel that may contain one or more antennas 12, sources, sensors [sensor/detector are interchangeable terms as used herein], magnets, a gamma-ray detector/generator assembly, neutron-generating/detecting assembly, various electronics, batteries, a downhole processor, a clock, a read-out port, and recording memory (not shown).

[0062] The RIT 10 does not have the mechanical requirements of

a drill collar. Thus, its mechanical constraints are greatly reduced. The RIT 10 has a landing mechanism (stinger) 14 on the bottom end and a fishing head 16 on the top. The fishing head 16 allows for the RIT 10 to be captured and retrieved from within a sub with the use of a conventional extraction tool such as the one described in U.S. Pat. No. 5,278,550 (assigned to the present assignee). An advantage of the fishable RIT 10 assembly is a reduction of Lost-In-Hole costs.

[0063] As shown in FIG. 2a, each antenna 12 on the RIT 10 consists of multi-turn wire loops encased in fiberglass-epoxy 18 mounted in a groove in the RIT 10 pressure housing and sealed with rubber over-molding 20. A feed-through 22 provides a passage for the antenna 12 wiring, leading to an inner bore 24 within the RIT 10. Each antenna 12 may be activated to receive or transmit an electromagnetic (EM) signal as known in the art.

[0064] The antennas 12 radiate an azimuthal electric field. Each antenna 12 is preferably surrounded by a stainless-steel shield 26 (similar to those described in U.S. Pat. No. 4,949,045, assigned to the present assignee) that has one or more axial slots 28 arrayed around the shield 26 circumference. FIG. 2b shows the axial slots 28 distributed

around the circumference of the shield 26. The shields 26 are short-circuited at the axial ends into the metal mandrel body of the RIT 10. These shields 26 permit transverse electric (TE) radiation to propagate through while blocking transverse magnetic (TM) and transverse electromagnetic (TEM) radiation. The shields 26 also protect the antennas 12 from external damage. The RIT 10 electronics and sensor architecture resembles that described in U.S. Pat. No. 4,899,112 (assigned to the present assignee).

[0065] *Sub* FIG. 3 shows an embodiment of a sub 30 of the invention. The sub 30 has an elongated body with tubular walls and a central bore 32. The sub 30 contains neither electronics nor sensors and is fully metallic, preferably formed from stainless steel. It is part of the normal bottom hole assembly (BHA), and it is in the hole with the drill string for the duration of the bit run. The sub 30 has normal threaded oilfield connections (pin and box) at each end (not shown).

[0066] The sub 30 includes one or more stations 36 with one or more axial slots 38 placed along the tubular wall. Each elongated axial slot 38 fully penetrates the tubular wall of the sub 30 and is preferably formed with fully rounded ends. Stress modeling has shown that rather long slots 38

may be formed in the sub 30 walls while still maintaining the structural integrity of the sub 30. Stress relief grooves 40 may be added to the OD of the sub 30, in regions away from the slot(s) 38, to minimize the bending moment on the slot(s) 38.

[0067] Each slot 38 provides a continuous channel for electromagnetic energy to pass through the sub 30. The slots 38 block TM radiation but allow the passage of TE radiation, albeit with some attenuation. The degree of attenuation of TE fields by the sub 30 depends on factors such as frequency, the number of slots, slot width, slot length, collar OD and ID, and the location and dimensions of the RIT 10 antenna. For example, FIG. 5 shows the sub 10 attenuation measured at 400 kHz with a 25-turn 1.75-inch diameter coil centered in 3.55-inch ID, 6.75-inch OD subs 30 with one or two slots 38 of different lengths and widths. As evident from FIG. 5, adding more slots 38 and making the slots longer or wider decreases the attenuation. However, with only one or two 0.5-inch wide 6–8 inch long slots 38, the sub 30 attenuation is already ~15 dB, which is sufficiently low for many applications.

[0068] In operation, the RIT 10 is pumped down and/or lowered through the drillstring on cable at the end of the bit run

and engaged inside the sub 30. The RIT 10 is received by a landing "shoe" 42 within the central bore 32 of the sub 30, as shown in FIG. 4a. FIG. 4b, shows how the RIT 10 is located in the sub 30 so that each antenna 12, source, or sensor is aligned with a slot 38 in the sub 30. The landing shoe 42 preferably also has a latching action to prevent any axial motion of the RIT 10 once it is engaged inside the sub 30.

[0069] Turning to FIG. 6, an embodiment of the invention includes a centralizer 44, which serves to keep the RIT 10 centered and stable within the sub 30, lowering shock levels and reducing the effects of tool motion on the measurement. One or more centralizers 44 may be mounted within the central bore 32 to constrain the RIT 10 and keep it from hitting the ID of the sub 30. One or more spring-blades 46 may also be mounted to extend from the centralizer 44 to provide positioning stability for the RIT 10. The spring-blades 46 are compressed against the RIT 10 when it is engaged within the sub 30. Bolts 48 with O-ring seals 50 may be used to hold the centralizer(s) 44 in the sub 30 while preserving the pressure barrier between the ID and the OD of the sub 30.

[0070] Alternatively, the centralizer 44 may be mounted on the

RIT 10 rather than on the sub 30 (See FIG. 16). In this case, the centralizer 44 may be configured to remain in a retracted mode during the trip down, and to open when the RIT 10 lands in the sub 30. It will be understood that other centralizer 44 configurations may be implemented with the invention as known in the art.

[0071] The RIT 10 and sub 30 have EM properties similar to a coaxial cable, with the RIT 10 acting as the inner conductor, and the sub 30 acting as the outer conductor of a coaxial cable. If the drilling mud is conductive, then the "coax" is lossy. If the drilling mud is oil based, the "coax" will have little attenuation. Parasitic antenna 12 coupling may take place inside of the sub 30 between receiver-receiver or transmitter-receiver. As described above, the shields 26 surrounding the antennas 12 are grounded to the mandrel of the RIT 10 to minimize capacitive and TEM coupling between them. Electrically balancing the antennas 12 also provides for TEM coupling rejection. The centralizers 44 may also be used as a means of contact to provide radio-frequency (rf) short-circuits between the RIT 10 and the sub 30 to prevent parasitic coupling. For example, small wheels with sharp teeth may be mounted on the centralizers 44 to ensure a hard short between the

RIT 10 and the sub 30 (not shown).

[0072] *Pressure Barrier* Since each slot 38 fully penetrates the wall of the sub 30, an insulating pressure barrier is used to maintain the differential pressure between the inside and the outside of the sub 30 and to maintain hydraulic integrity. There are a variety of methods for establishing a pressure barrier between the sub 30 ID and OD at the slotted station 36.

[0073] Turning to FIG. 7a, an embodiment of a sub 30 with a pressure barrier of the invention is shown. A cylindrical sleeve 52 is positioned within the central bore 32 of the sub 30 in alignment with the slot(s) 38. The sleeve 52 is formed of a material that provides transparency to EM energy. Useable materials include the class of polyetherketones described in U.S. Pat. No. 4,320,224, or other suitable resins. *Victrex USA, Inc.* of West Chester, PA manufactures one type called PEEK. Another usable compound is known as PEK. *Cytec Fiberite*, *Greene Tweed*, and *BASF* market other suitable thermoplastic resin materials. Another useable material is Tetragonal Phase Zirconia ceramic (TZP), manufactured by *Coors Ceramics*, of Golden, Colorado. It will be appreciated by those skilled in the art that these and other materials may be combined to form a useable

sleeve 52.

[0074] PEK and PEEK can withstand substantial pressure loading and have been used for harsh downhole conditions. Ceramics can withstand substantially higher loads, but they are not particularly tolerant to shock. Compositions of wound PEEK or PEK and glass, carbon, or KEVLAR may also be used to enhance the strength of the sleeve 52.

[0075] A retainer 54 and spacer 56 are included within the central bore 32 to support the sleeve 52 and provide for displacement and alignment with the slots 38. The sleeve 52 is positioned between the retainer 54 and spacer 56, which are formed as hollow cylinders to fit coaxially within the central bore 32. Both are preferably made of stainless steel. The retainer 54 is connected to the sleeve 52 at one end, with the sleeve 52 fitting coaxially inside the retainer 54. As the differential pressure increases within the ID of the sub 30 during operation, the sleeve 52 takes the loading, isolating the sub 30 from the pressure in the slotted region. Hydraulic integrity is maintained at the junction between the sleeve 52 and retainer 54 by an O-ring seal 53. A fitted "key" 55 is used to engage the sleeve 52 to the retainer 54, preventing one from rotating relative to the other (See FIG. 7a blow-up). An index pin 57 is fitted

through the sub 30 and engaged to the free end of the retainer 54 to prevent the retainer from rotating within the bore 32 of the sub 30. O-rings 59 are also placed within grooves on the OD of the retainer 54 to provide a hydraulic seal between the retainer 54 and the sub 30.

[0076] In operation, the internal sleeve 52 will likely undergo axial thermal expansion due to high downhole temperatures. Thus, it is preferable for the sleeve 52 to be capable of axial movement as it undergoes these changes in order to prevent buckling. The spacer 56 consists of an inner cylinder 60 within an outer cylinder 62. A spring 64 at one end of the OD of the inner cylinder 60 provides an axial force against the outer cylinder 62 (analogous to an automotive shock absorber). The outer cylinder 62 is connected to the sleeve 52 using the key 55 and O-ring seal 53 at the junction as described above and shown in the blow-up in FIG. 7a. The spring-loaded spacer 56 accounts for differential thermal expansion of the components. The sub 30 embodiment of FIG. 7a is shown connected to other tubular members by threaded oilfield connections 70.

[0077] For purposes of illustration, a sub 30 with only one slot 38 is shown in FIG. 7a. Other embodiments may include

several sleeves 52 interconnected in the described manner to provide individual pressure barriers over multiple slotted stations 36 (not shown). With this configuration, only two O-ring 53 seals to the ID of the sub 30 are used over the entire slotted array section. This minimizes the risk involved with dragging the O-rings 53 over the slots 38 during assembly or repair. FIG. 7b shows a cross-section of the sub 30 (along line A-A of FIG. 7a) with a three-slot 38 configuration.

[0078] FIG. 8a shows another embodiment of a sub 30 with a pressure barrier of the invention. In this embodiment, the spring-loaded spacer 56 maintains the outer cylinder 62 abutted against the sleeve 52 and O-rings 68 are placed within grooves on the OD of the sleeve 52, preferably at both ends of the slot 38. The retainer 54 rests at one end against a shoulder or tab 58 formed on the wall of the central bore 32. FIG. 8b shows a cross-section of the sub 30 (along line B-B of FIG. 8a) with a three-slot 38 configuration.

[0079] In another embodiment of a pressure barrier of the invention, a sleeve 52 made out of PEEK or PEK, or glass, carbon, or KEVLAR filled versions of these materials, may be bonded to a metal insert (not shown), where the insert

contains O-rings to seal against the sub 30 as described above. The metal insert could be mounted within the sub 30 as described above or with the use of fastener means or locking pins (not shown). The sleeve material may also be molded or wrapped onto the supporting insert. The fibers in the wrapped material can also be aligned to provide additional strength.

[0080] FIG. 9a shows another embodiment of a pressure barrier of the invention. In this embodiment, the cylindrical sleeve 52 is held in alignment with the slot(s) 38 by a metal retainer 72. The retainer 72 may be formed as a single piece with an appropriate slot 74 cut into it for signal passage as shown, or as independent pieces supporting the sleeve 52 at the top and bottom (not shown). The retainer 72 may be constrained from axial movement or rotation within the sub 30 by any of several means known in the art, including an index-pin mechanism or a keyed-jam-nut type arrangement (not shown). The slot 38 may also be filled with a protective insert as will be further described below. In operation, a RIT 10 is positioned within the sub 30 such that the antenna 12 is aligned with the slot(s) 38.

[0081] As shown in FIG. 9b, the retainer 72 is formed such that it

extends into and reduces the ID of the sub 30 to constrain the RIT 10. Mudflow occurs through several channels or openings 76 in the retainer 72 and through the annulus 78 between the RIT 10 and the retainer 72. The retainer 72 in effect acts as a centralizer to stabilize the RIT 10 and to keep it from hitting the ID of the sub 30, lowering shock levels and increasing reliability.

[0082] FIG. 10 shows another embodiment of a pressure barrier of the invention. A sub 30 may be formed with a shop joint 80 so that the sleeve 52 can be inserted within the central bore 32. The sleeve 52 is formed as described above and provides a hydraulic seal using O-rings 82 within grooves at both ends on the OD of the sleeve 52. The sleeve 52 is restrained from axial movement within the central bore 32 by a lip 84 formed on one end of the two-piece sub 30 and by the end of the matching sub 30 joint. Since the sleeve 52 sits flush within a recess 86 in the ID of the sub 30, this configuration offers unrestricted passage to a large diameter RIT 10. This configuration also provides easy access to the sleeve 52 and slot(s) 38 for maintenance and inspection.

[0083] Turning to FIG. 11, another embodiment of a pressure barrier of the invention is shown. The slot 38 in the sub

30 is three-stepped, preferably with fully rounded ends. One of the steps provides a bearing shoulder 90 for an insert 92, and the other two surfaces form the geometry for an O-ring groove 94 in conjunction with the insert 92. A modified O-ring seal consists of an O-ring 96 stretched around the insert 92 at the appropriate step, with metal elements 98 placed on opposite sides of the O-ring 96. The metal elements 98 are preferably in the form of closed loops.

[0084] The sleeve 52 may be fitted within the sub 30 with one or more O-rings (not shown) to improve hydraulic integrity as described above. As shown in FIG. 11, the sleeve 52 may also have a slot 100 penetrating its wall to provide an unobstructed channel for any incoming or outgoing signal. The sleeve 52 may have a matching slot 100 for every slot 38 in the sub 30.

[0085] The insert 92 and sleeve 52 are preferably made of the dielectric materials described above to permit the passage of EM energy. However, if the sleeve 52 is configured with a slot 100, the sleeve 52 may be formed from any suitable material.

[0086] If the sleeve 52 is configured with a slot 100, the internal pressure of the sub 30 may push the insert 92 outward.

The bearing shoulder 52 takes this load. As the internal pressure increases, the O-ring 96 pushes the metal elements 98 against an extrusion gap, which effectively closes off the gap. As a result, there is no room for extrusion of the O-ring 96. Since the metal is much harder than the O-ring material, it does not extrude at all. The modified geometry therefore creates a scenario where a soft element (the O-ring) provides the seal and a hard element (the metal loop) prevents extrusion, which is the ideal seal situation. In the event of pressure reversal, the sleeve 52 captures the insert 92 in the slot 38, preventing the insert 92 from being dislodged.

[0087] Other pressure barrier configurations may be implemented with the invention. One approach is the use of several individual sleeves 52 connected together by other retaining structures and restrained by a pressure-differential seal or a jam-nut arrangement (not shown). Another approach is the use of a long sleeve 52 to span multiple slotted stations 38 (not shown). Still another approach is the use of a sleeve 52 affixed to the OD of the sub 30 over the slotted region, or a combination of an interior and exterior sleeve 52 (not shown).

[0088] *Slot Inserts* While the slotted stations of the invention are

effective with fully open and unblocked slots 38, the operational life of the assembly may be extended by preventing debris and fluids from entering and eroding the slots 38 and the insulating sleeve 52. The slots 38 could be filled with rubber, an epoxy-fiberglass compound, or another suitable filler material to keep fluids and debris out while permitting signal passage.

[0089] An embodiment of a sub 30 with a tapered slot 38 is shown in FIG. 12a. The slot 38 is tapered such that the outer opening W_1 is narrower than the inner opening W_2 , as shown in FIG. 12b. A tapered wedge 88 of insulating material (e.g., fiberglass epoxy) is inserted within the tapered slot 38. The wedge 88 may be bonded into the sub 30 with rubber. The rubber layer surrounds the wedge 88 and bonds it into the sub 30. An annulus of rubber may also be molded on the interior and/or exterior surface of the sub 30 to seal the wedge 88 within the slot 38.

[0090] *Focusing Shield Structures* Measurements of the attenuation of the TE radiation from a simple coil-wound antenna 12 through a single slot 38 of reasonable dimensions show that the TE field is notably attenuated. This attenuation can be reduced, however, by using shielding around the antenna 12 to focus the EM fields into the slot 38.

- [0091] Turning to FIG. 13a, an antenna 12 consisting of 25 turns of wire on a 1.75-inch diameter bobbin was mounted on a 1-inch diameter metal RIT 10 and positioned fully eccentrically inside the bore of a 3.55-inch ID, 6.75-inch OD sub 30 against the slot 38 and centered vertically on the slot 38. The measured attenuation of the TE field between 25 kHz 2 MHz was a nearly constant 16.5 dB.
- [0092] Turning to FIG. 13b, the same measurement was performed with the antenna 12 inside a thin shield 102 formed of a metallic tube with a 0.5-inch wide, 6-inch long slot 104 aligned with the slot 38 in the sub 30 (not shown). The antenna 12 was fully surrounded by the shield 102 except for the open slot 104 and placed inside the sub 30.
- [0093] The attenuation with this assembly in the same sub 30 was 11.8 dB, a reduction of the attenuation of nearly 5 dB. FIGS. 13b and 13c respectively show how the shield 102 affects the magnetic and electric fields. The attenuation due to this shield 102 alone is minimal.
- [0094] FIG. 14 shows another embodiment of a shielding structure of the invention. In this embodiment, the central bore 32 of the sub 30 is configured with a bracket structure 106 that serves as a focusing shield by surrounding the

antenna 12 when the RIT 10 is engaged within the sub 30.

[0095] FIG. 15 shows another embodiment of a shielding structure of the invention. The mandrel of the RIT 10 has a machined pocket or cavity 108 in its body. A coil antenna 12 wound on a bobbin 110 made of dielectric material is mounted within the cavity 108. A ferrite rod may replace the dielectric bobbin 110. With this configuration, the body of the RIT 10 itself serves as a focusing shield. The hydraulic integrity of the RIT 10 is maintained by potting the antenna 12 with fiberglass-epoxy, rubber, or another suitable substance. The attenuation of a coil antenna 12 having 200 turns on a 0.875-inch diameter bobbin was measured for this assembly mounted the same way as described above in the same sub 30. The measured attenuation was only ~7 dB. It will be appreciated by those skilled in the art that other types of sources/sensors may be housed within the cavity 108 of the RIT 10.

[0096] *RIT / Sub Configurations* FIG. 16 shows another embodiment of the invention. A sub 30 of the invention is connected to another tubular 111 forming a section of a drillstring. The RIT 10 includes an antenna 12, a stinger 14 at the lower end, and a fishing head 16 at the top end. The stinger 14 is received by the landing shoe 42 on the sub 30, which

serves to align the antenna 12 with the slotted station 36. As above, the RIT 10 of this embodiment includes various electronics, batteries, a downhole processor, a clock, a read-out port, memory, etc. (not shown) in a pressure housing. The RIT 10 may also incorporate various types of sources/sensors as known in the art.

[0097] *RIT with Modulator* The RIT 10 of FIG. 16 is also equipped with a modulator 116 for signal communication with the surface. As known in the art, a useable modulator 116 consists of a rotary valve that operates on a continuous pressure wave in the mud column. By changing the phase of the signal (frequency modulation) and detecting these changes, a signal can be transmitted between the surface and the RIT 10. With this configuration, one can send the RIT 10 through the drillstring to obtain measurement data (e.g., resistivity or gamma-ray counts) of formation characteristics and to communicate such data to the surface in real-time. Alternatively, all or some of the measurement data may be stored downhole in the RIT 10 memory for later retrieval. The modulator 116 may also be used to verify that the RIT 10 is correctly positioned in the sub 30, and that measurements are functioning properly. It will be appreciated by those skilled in the art that a modulator

116 assembly may be incorporated with all of the RIT/sub implementations of the invention.

[0098] FIG. 17 shows another embodiment of the invention. The subs 30 and RITs 10 of the invention may be used to communicate data and/or instructions between the surface and a remote tool 112 located along the drill string. For purposes of illustration, the tool 112 is shown with a bit box 113 at the bottom portion of a drive shaft 114. The drive shaft 114 is connected to a drilling motor 115 via an internal transmission assembly (not shown) and a bearing section 117. The tool 112 also has an antenna 12 mounted on the bit box 113. The motor 115 rotates the shaft 114, which rotates the bit box 113, thus rotating the antenna 12 during drilling.

[0099] With the configuration of FIG. 17, the RIT 10 may be engaged within the sub 30 at the surface or sent through the drill string when the sub 30 is at a desired downhole position. Once engaged, a wireless communication link may be established between the antenna 12 on the RIT 10 and the antenna 12 on the tool 112, with the signal passing through the slotted station 36. In this manner, real-time wireless communication between the surface and the downhole tool 112 may be established. It will be appreci-

ated by those skilled in the art that other types of sensors and/or signal transmitting/receiving devices may be mounted on various types of remote tools 112 for communication with corresponding devices mounted on the RIT 10.

[0100] *Nuclear Magnetic Resonance Sensing* It is known that when an assembly of magnetic moments such as those of hydrogen nuclei are exposed to a static magnetic field they tend to align along the direction of the magnetic field, resulting in bulk magnetization. By measuring the amount of time for the hydrogen nuclei to realign their spin axes, a rapid nondestructive determination of porosity, movable fluid, and permeability of earth formations is obtained. See A. Timur, *Pulsed Nuclear Magnetic Resonance Studies of Porosity, Movable Fluid, and Permeability of Sandstones*, Journal of Petroleum Technology, June 1969, p. 775. U.S. Pat. No. 4,717,876 describes a nuclear magnetic resonance well logging instrument employing these techniques.

[0101] A determination of formation porosity from magnetic resonance may be obtained with a non-magnetic sub 30 of the invention as shown in FIG. 18. The sub 30 can be formed of the typical high-strength non-magnetic steel used in the industry. The RIT 10 contains the electronics,

batteries, CPU, memory, etc., as described above. Opposing permanent magnets 118 contained in the RIT 10 provide the magnetic field. A rf coil 120 is mounted between the magnets 118 for generating a magnetic field in the same region to excite nuclei of the formation vicinity. The design of the rf coil 120 is similar to the antennas 12 described above in being a multi-turn loop antenna with a central tube for through wires and mechanical strength. The permanent magnets 118 and rf coil 120 are preferably housed in a non-magnetic section of the sub 30 that has axial slots 38 with a pressure barrier (not shown) of the invention.

[0102] With a non-magnetic sub 30, the static magnetic fields B_0 from the permanent magnets 118 penetrate into the surrounding formation to excite the nuclei within the surrounding formation. The coil 120 in the RIT 10 provides a rf magnetic field B_1 , which is perpendicular to B_0 outside of the sub 30. The rf coil 120 is positioned in alignment with the axial slot(s) 38 in the sub 30.

[0103] A magnetic resonance measurement while tripping may be more complicated in comparison to propagation resistivity measurements due to various factors, including: an inherently lower signal-to-noise ratio, permanent magnet form

factors, rf coil efficiency, high Q antenna tuning, high power demands, and a slower logging speed.

[0104] *Gamma-Ray Measurement* It is known that gamma ray transport measurements through a formation can be used to determine its characteristics such as density. The interaction of gamma rays by Compton scattering is dependent only upon the number density of the scattering electrons. This in turn is directly proportional to the bulk density of the formation. Conventional logging tools have been implemented with detectors and a source of gamma rays whose primary mode of interaction is Compton scattering. *See*, U.S. Pat. No. 5,250,806, assigned to the present assignee. Gamma ray formation measurements have also been implemented in LWT technology. *See*, "Logging while Tripping Cuts Time to Run Gamma Ray", Oil & Gas Journal, June 1996, pp. 65–66. The present invention may be used to obtain gamma-ray measurements as known in the art, providing advantages over known implementations.

[0105] The subs 30 of the invention provide the structural integrity required for drilling operations while also providing a low-density channel for the passage of gamma rays. Turning to FIG. 4b, this configuration is used to illustrate a gamma-ray implementation of the invention. In this im-

plementation, a RIT 10 is equipped with a gamma-ray source and gamma-ray detectors (not shown) of the type known in the art and described in the '806 patent. The antennas 12 of FIG. 4b would be replaced with a gamma-ray source and gamma-ray detectors (not shown).

[0106] Two gamma-ray detectors are typically used in this type of measurement. The gamma-ray detectors are placed on the RIT 10 at appropriate spacings from the source as known in the art. The slotted stations 36 are also appropriately placed to match the source and detector positions of the RIT 10. Calibration of the measurement may be required to account for the rays transmitted along the inside of the sub 30. The gamma-ray detectors may also be appropriately housed within the RIT 10 to shield them from direct radiation from the source as known in the art.

[0107] Turning to FIG. 14, this configuration is used to illustrate another gamma-ray implementation of the invention. With the RIT 10 equipped with the described gamma-ray assembly and eccentered toward the slots 38, this configuration will capture the scattered gamma rays more efficiently and provide less transmission loss.

[0108] *Resistivity Measurement* The invention may be used to measure formation resistivity using electromagnetic propaga-

tion techniques as known in the art, including those described in U.S. Pats. Nos. 5,594,343 and 4,899,112 (both assigned to the present assignee). FIGS. 19a and 19b show two RIT 10 / sub 30 configurations of the invention. A pair of centrally located receiver antennas Rx are used to measure the phase shift and attenuation of EM waves. Look-up tables may be used to determine phase shift resistivity and attenuation resistivity. Transmitter antennas Tx are placed above and below the receiver antennas Rx, either in the configuration shown in FIG. 19a, which has two symmetrically placed transmitter antennas Tx, or in the configuration shown in FIG. 19b, which has several transmitter antennas Tx above and below the receiver antennas Rx. The architecture of FIG. 19a can be used to make a borehole compensated phase-shift and attenuation resistivity measurement, while the multiple Tx spacings of FIG. 19b can measure borehole compensated phase-shift and attenuation with multiple depths of investigation. It will be appreciated by those skilled in the art that other source/sensor configurations and algorithms or models may be used to make formation measurements and determine the formation characteristics.

[0109] *Inductively-Coupled RIT / Sub* Turning to FIG. 20, other em-

bodiments of a sub 30 and RIT 10 of the invention are shown. The sub 30 contains one or more integral antennas 12 mounted on the OD of the elongated body for transmitting and/or receiving electromagnetic energy. The antennas 12 are embedded in fiberglass epoxy, with a rubber over-molding as described above. The sub 30 also has one or more inductive couplers 122 distributed along its tubular wall.

[0110] The RIT 10 has a small-diameter pressure housing such as the one described above, which contains electronics, batteries, downhole processor, clocks, read-out port, recording memory, etc., and one or more inductive couplers 122 mounted along its body.

[0111] As shown in FIG. 21, the RIT 10 is eccentric inside the sub 30 so that the inductive coupler(s) 122 in the RIT 10 and the inductive coupler(s) 122 in the sub 30 are in close proximity. The couplers 120 consist of windings formed around a ferrite body as known in the art. Feed-throughs 124 connect the antenna 12 wires to the inductive coupler 122 located in a small pocket 126 in the sub 30. A metal shield 128 with vertical slots covers each antenna 12 to protect it from mechanical damage and provide the desired electromagnetic filtering properties as previously

described. Correctly positioning the RIT 10 inside the sub 30 improves the efficiency of the inductive coupling. Positioning is accomplished using a stinger and landing shoe (See FIG. 4a) to eccentric the RIT 10 within the sub 30. It will be appreciated by those skilled in the art that other eccentricing systems may be used to implement the invention.

[0112] As shown in FIG. 22a, the inductive couplers 122 have "U" shaped cores made of ferrite. The ferrite core and windings are potted in fiberglass-epoxy, over molded with rubber 131, and mounted within a coupler package 130 formed of metal. The coupler package 130 may be formed of stainless steel or a non-magnetic metal. Standard O-ring seals 132 placed around the inductive coupler package 130 provide a hydraulic seal. The inductive couplers 122 in the RIT 10 may also be potted in fiberglass-epoxy and over molded with rubber 131. A thin cylindrical shield made of PEEK or PEK may also be placed on the OD of the sub 38 to protect and secure the coupler package 130 (not shown).

[0113] In operation, there will be a gap between the inductive couplers 122 in the RIT 10 and the sub 30, so the coupling will not be 100% efficient. To improve the coupling

efficiency, and to lessen the effects of mis-alignment of the pole faces, it is desirable for the pole faces to have as large a surface area as possible.

[0114] FIG. 22b shows a 3.75-inch long by 1-inch wide slot 38 in the sub 30. The pole face for this inductive coupler 122 is 1.1-inches long by 0.75-inch wide, giving an overlap area of 0.825 square inches. This configuration maintains a high coupling efficiency and reduces the effects due to the following: movement of the RIT 10 during drilling or tripping, variations in the gap between the inductive couplers 122, and variations in the angle of the RIT 10 with respect to the sub 30. Another advantage of a long slot 38 design is that it provides space for the pressure feed-throughs 124 in the inductive coupler package 130.

[0115] Antenna tuning elements (capacitors) may also be placed in this package 130 if needed. It will be appreciated by those skilled in the art that other aperture configurations may be formed in the walls of the sub 30 to achieve the desired inductive coupling, such as the circular holes shown in FIG. 20.

[0116] Since the pressure inside the sub 30 will be 1–2 Kpsi higher than outside the sub 30 in most cases, the inductive coupler package 130 should be mechanically held in

place. Turning to FIG. 23, the antenna shield 128 can be used to retain the inductive coupler package 130 in place. The shield 128 having slots over the antenna 12 as described above, but solid elsewhere. The solid portion retains the inductive coupler package 130 and takes the load from the differential pressure drop. Tabs may also be placed on the outside of the inductive coupler package 130 to keep it from moving inward (not shown). The shield 128 may also be threaded on its ID, with the threads engaging matching "dogs" on the sub 30 (not shown).

[0117] FIG. 24 shows a simple circuit model for an embodiment of the inductive coupler and transmitter antenna of the invention. On the RIT 10 side, the current is I_1 , and the voltage is V_1 . On the sub 30 side, the current is I_2 and the voltage is V_2 . The mutual inductance is M , and the self-inductance of each half is L . This inductive coupler is symmetric with the same number of turns on each half. With the direction of I_2 defined in FIG. 24, the voltage and currents are related by $V_1 = j\omega L I_1 + j\omega M I_2$ and $V_2 = j\omega M I_1 + j\omega L I_2$. The antenna impedance is primarily inductive (L_A) with a small resistive part (R_A),

$$Z_A = R_A + j\omega L_A$$

Typically the inductive impedance is about 100 Ω , while the resistive impedance is about 10 Ω . A tuning capacitor (C) may be used to cancel the antenna inductance, giving a RIT side impedance $Z_2 = R_A + j\omega L_A - j/\omega C \sim R_A$. The ratio of the current delivered to the antenna to the current driving the inductive coupler is $I_2/I_1 = -j\omega M/(j\omega L + R_A + j\omega L_A - j/\omega C)$. The inductive coupler has many turns and a high permeability core, so $L \gg L_A$ and

$$\omega L \gg R_A$$

To good approximation, $I_2/I_1 = \sim -M/L$ (the sign being relative to the direction of current flow in FIG. 24).

[0118] *Implementations of the Invention* As described above, the RIT 10 may be equipped with internal data storage means such as conventional memory and other forms of the kind well known in the art or subsequently developed. These storage means may be used to communicate data and/or instructions between the surface and the downhole RIT 10. Received signal data may be stored downhole within the storage means and subsequently retrieved when the RIT 10 is returned to the surface. As known in the art, a computer (or other recording means) at the surface keeps track of time versus downhole position of the sub so that stored data can be correlated with a downhole location.

Alternatively, the signal data and/or instructions may be communicated in real-time between the surface and the RIT 10 by LWD/MWD telemetry as known in the art.

[0119] FIG. 25 illustrates a flow diagram of a method 300 for transmitting and/or receiving a signal through an earth formation in accord with the invention. The method comprises drilling a borehole through the earth formation with a drill string, the drill string including a sub having an elongated body with tubular walls and including at least one station having at least one slot formed therein, each at least one slot fully penetrating the tubular wall to provide a continuous channel for the passage of electromagnetic energy 305; engaging a run-in tool within the sub, the run-in tool being adapted with signal transmitting means and/or signal receiving means 310; locating the run-in tool within the sub such that at least one signal transmitting or receiving means is aligned with at least one slotted station on the sub 315; and transmitting or receiving a signal through the formation, respectively via the transmitting or receiving means 320.

[0120] FIG. 26 illustrates a flow diagram of a method 400 for measuring a characteristic of an earth formation surrounding a borehole in accord with the invention. The

method comprises adapting a downhole tool with at least one signal transmitting means and at least one signal receiving means 405; adapting the downhole tool with end means capable of accepting a fishing head or a cable connection 410; and with the fishing head on the tool, engaging the tool within a drill string to measure the formation characteristic, utilizing the transmitting and receiving means, as the drill string traverses the borehole; with the cable connection on the tool, connecting a cable to the tool and suspending the tool within the borehole to measure the formation characteristic utilizing the transmitting and receiving means 420.

[0121] The method 400 of FIG. 26 may be implemented with the run-in tools 10 and subs 30 of the invention. The run-in tool may be configured with an end segment or cap (not shown) adapted to receive the previously described fishing head or a cable connection. With the fishing head connected to the run-in tool, the tool may be used in accordance with the disclosed implementations. With the cable connection, the run-in tool may be used as a memory-mode wireline tool.

[0122] It will be understood that the following methods for sealing an opening or slot on the surface of a tubular are

based on the disclosed pressure barriers and slot inserts of the invention.

[0123] FIG. 27 illustrates a flow diagram of a method 500 for sealing an opening on the surface of a tubular, wherein the tubular has an elongated body with tubular walls and a central bore. The method comprises placing an insert within the opening, the insert being formed in the shape of the opening 505; and applying a bonding material to the insert and/or opening to bond the insert within the opening 510.

[0124] FIG. 28 illustrates a flow diagram of a method 600 for sealing a fully penetrating opening on the surface of a tubular having an elongated body with tubular walls and a central bore. The method comprises placing an insert within the opening, the insert being formed in the shape of the opening 605, and placing retainer means within the tubular to support the insert against the opening 610.

[0125] *Nuclear Source Measurements* As previously described, the RITs 10 of the invention may be implemented with one or more radiation sources and one or more radiation sensors to provide nuclear (e.g. density or neutron porosity) formation evaluation. FIG. 29 shows another embodiment of the invention. In this embodiment, the RIT 10 includes a

neutron source 134 and two neutron detectors 136, 138 (e.g. He3 detectors). The neutron source 134 may be any one of the type well known in the logging industry such as an encapsulated chemical source (e.g. AmBe source) or an accelerator neutron generator such as described in U.S. Pat. No. 5,235,185 (assigned to the present assignee). The RIT 10 is also equipped with batteries, electronics, controllers, memory, a real-time clock, and read-out ports as described above. The source 134 and detectors 136, 138 may be disposed within the RIT 10 in conventional configurations such as described in U.S. Pat. Nos. 4,879,463, Re36,012, 5,608,215, 5,767,510, 5,804,820, 6,032,102, and 6,285,026 (all assigned to the present assignee). These patents also describe various subsurface measurements that can be implemented with embodiments of the invention.

[0126] The neutrons emitted by the source 134 produce secondary radiations in the borehole and formations as a result of the nuclei interactions. The term "secondary radiation" is used to include neutrons scattered by the borehole contents and by the formations (e.g. thermal or epithermal neutrons) or gamma rays resulting from neutron capture by the formation nuclei.

[0127] The RIT 10 of FIG. 29 also includes a gamma-ray source 140 and gamma-ray detectors 142, 144. The source 140 may be any conventional type such as an encapsulated quantity of cobalt or cesium, or any other radioactive substance that produces gamma rays in its decay. The source 140 may be located either inside the RIT, or in a side-hole (not shown) to facilitate wellsite loading. Gamma rays from the source 140 are focused toward the formation by shielding 148 (see FIG. 30) as known in the art. The detectors 142, 144 may be any conventional type as well, e.g. NaI scintillation crystals 145 coupled to photomultiplier tubes 147 (see FIG. 30). The shields 148 also provide directional sensitivity to the detectors. Usable shielding materials include bismuth, lead, tungsten alloy or other materials that are opaque to gamma-ray radiation. U.S. Pat. No. 5,250,806 (assigned to the present assignee) further describes logging apparatus equipped with gamma-ray sources.

[0128] Since the metallic sub 30 body will limit or prevent the passage of gamma-ray energy from the source to the formation, partially penetrating windows 150 are formed in the sub 30 wall. These windows 150 are fluidly sealed with a suitable radiation-transparent or low-density ma-

terial such as plugs of epoxy, RANDOLITE, or beryllium. Because the pressure drop from the interior to the exterior of the sub 30 is small, these windows 150 can be large in diameter. As described above with reference to FIG. 4b, other embodiments for nuclear-based measurements can be implemented with subs 30 adapted with fully-penetrating openings 38. Any of the pressure barriers of the invention can be used to provide a seal for the fully-penetrating openings. For example, low density sleeves of metal or composite sleeves may be used as described herein.

[0129] The embodiment of FIG. 29 shows a sub 30 with an integral stabilizer blade 152 extending outward from the sub body. In this embodiment, the partially penetrating windows 150 are disposed in the stabilizer blade 152. U.S. Pat. No. 4,879,463 describes a logging tool equipped with windowed stabilizer blades. Other gamma-ray-source embodiments of the invention may be configured using a sub 30 without stabilizer blades 152, such as previously described with respect to FIG. 4b. These embodiments are implemented using a "slick" sub 30 equipped with slots 38 and/or with partially penetrating windows 150.

[0130] By rotating the radiation-sourced sub 30 as it is tripped

out of the borehole (e.g. with a top drive), azimuthal density measurements can be obtained. The RIT 10 can be equipped with magnetometers as known in the art to determine the borehole and formation properties as a function of angular segments defined around the 360-degree circumference of the sub 30. U.S. Pat. Nos. 5,473,158 and 5,513,528 (both assigned to the present assignee) describe apparatus configured with nuclear sources to make such measurements while drilling.

[0131] Density measurements with a retrievable system entail special considerations. There is a possibility of gamma rays leaking into the spaced detectors 142, 144 via the mud flow channel inside the sub 30. To minimize this effect, the RIT 10 is eccentric within the sub bore. FIG. 31 shows the eccentric RIT 10 with the cross-sectional area of the sub 30 closely fitting the RIT 10 OD. As previously discussed, the source 140 and detectors 142, 144 also have heavy shielding 148 on the side facing the mud flow channel, and openings in the shields on the side facing the formation. Standard calibration techniques can be used to reduce the effects of stray gamma rays.

[0132] Another consideration is misalignment between the RIT 10 and the sub 30, which could result in measurement errors.

The landing stinger 14 on the RIT engages with the landing shoe 42 such that the source 140 and detectors 142, 144 are each azimuthally and axially positioned within the sub and aligned with a window 150. Some embodiments of the invention may include centralizing springs 46 (shown in FIG. 29), or other landing mechanism as described herein and known in the art, to eccentrically and mechanically latch the RIT into place.

[0133] FIG. 32 shows another embodiment of the invention. The RIT 10 is equipped with another pair of gamma-ray detectors 154 that are used to measure the axial position of the RIT within the sub with greater precision. These two detectors 154 are simple counters; they do not measure the energy spectra. Useable detectors 154 include scintillators, solid state, or Geiger-Mueller detectors. The upper detector is labeled "1" and the lower "2". An angled inner passage 156 is drilled in the sub 30 wall. Though this particular embodiment shows the passage 156 formed within a stabilizer blade 152, it will be understood that other sub embodiments may have the inner passage formed in non-bladed walls (not shown).

[0134] The sub wall inner passage 156 forms two paths, one pointing downward toward the gamma-ray source 140 in

the RIT 10, the other points upward toward the mid-point between the gamma-ray detectors 154. These paths are filled with radiation transparent or low density material. A reflecting plug 158 is mounted in the sub wall to backscatter gamma rays from the source 140 back toward the sub bore and to the pair of detectors 154. The plug 158 may be formed of any suitable material, e.g. steel, and mounted within the sub in any suitable manner known in the art.

[0135] If the RIT 10 is perfectly aligned within the sub 30, then countrates in the two detectors 154 will be equal because the mid-point of the detectors is exactly in line with the passage 156 upper path, as illustrated in FIG. 33b. If the RIT is slightly higher in the sub than desired, then detector 1 is farther from the passage 156 upper path and has a lower countrate than detector 2 (FIG. 33a). Conversely, if the RIT is slightly lower in the sub than desired, then detector 1 is closer to the passage 156 upper path and has a higher countrate than detector 2 (FIG. 33c). Thus the ratio of the countrates in the detectors 154 indicates the position of the RIT in the sub (FIG. 33d). Since the RIT position should not change rapidly on the trip-out, the countrates can be acquired for a long period, thus providing high

statistical precision.

[0136] As known in the art, measurement reliability is improved by calibrating the instrument before the logging job. A calibration process for embodiments of the invention entails positioning the RIT 10 within the sub 30 so that the position-sensitive detectors 154 are centered with the upper path of the inner passage 156, and then placed a known distance high of center, and a known distance low of center. The RIT/sub is calibrated in blocks of known density by recording the countrates for the spaced detectors 142, 144 and for the position-sensitive detectors 154. Thus, the position-sensitive ratio can be calibrated with the axial displacement (FIG. 33d). The density calibration terms will also vary slightly with the axial displacement, and they can therefore be expressed as functions of the position-sensitive ratio (FIG. 33e). During logging, the position-sensitive ratio is used in the density measurement. From the measured ratio, the appropriate density correction terms are computed from the above functions.

[0137] It will be appreciated by those skilled in the art that the spacings between the sources 134, 140 and detectors 136, 138, 142, 144 on the RIT are variable depending on

the desired measurements. Extensive stand-off between the sub 30 and the formation may be corrected by using standard spine and ribs processing. Additional radiation detectors (e.g. a mid-spaced detector between the two detectors 142, 144) may also be incorporated into the RIT to overcome large stand-off errors as known in the art. As described above, the RIT embodiments of the invention are equipped with the electronics and components to provide the radiation sources and detectors with power and control for the desired nuclear measurements. It will also be appreciated that any of the known radiation data processing techniques may be used with the present invention.

[0138] The embodiment shown in FIG. 29 illustrates a retrievable "triple-combo" tool, equipped to provide electromagnetic, gamma-ray, neutron and density measurements. The RIT 10 is equipped with a fishing head 16 for trip-in on cable and retrieval if necessary. Thus both nuclear sources are recoverable by a fishing operation. Other embodiments may include and RIT and sub equipped with inductive couplers as previously described. Such embodiments could be used to verify that the RIT is properly located in the sub and functioning.

[0139] FIG. 34 illustrates a flow diagram of a method for determining a property of a subsurface formation traversed by a borehole in accord with the invention. The method includes adapting a sub for disposal within the borehole, the sub having an elongated body with tubular walls and an inner bore, the sub wall including an inner passage adapted to direct radiation energy emitted from within the sub back toward the sub bore 705; disposing a run-in tool within the sub bore, the tool having at least one radiation source and at least one radiation sensor disposed thereon 710; emitting radiation energy into the formation from the at least one radiation source on the run-in tool 715; and detecting radiation energy with the at least one radiation sensor on the run-in tool to determine the formation property 720.

[0140] The method of FIG. 34 may be implemented with the run-in tools 10 and subs 30 of the invention. The run-in tool may be configured with an end segment or cap (not shown) adapted to receive the previously described fishing head or a cable connection. With the fishing head connected to the run-in tool, the tool may be used in accord with the disclosed implementations. With the cable connection, the run-in tool may be used as a memory-mode

wireline tool.

[0141] While the methods and apparatus of this invention have been described as specific embodiments, it will be apparent to those skilled in the art that variations may be applied to the structures and in the steps or in the sequence of steps of the methods described herein without departing from the concept and scope of the invention. For example, it will be appreciated that although embodiments of the invention provide for retrievable logging systems, they may also be implemented in "normal" logging applications, i.e., the invention is not limited solely to LWT applications.